PEGASUS II EXPERIMENTS AND PLANS FOR THE ATLAS PULSED POWER FACILITY

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ABSTRACT

Atlas will be a high-energy (36 MJ stored), high-power (~ 10 TW) pulsed power driver for high energy-density experiments, with an emphasis on hydrodynamics. Scheduled for completion in late 1999, Atlas is designed to produce currents in the 40-50 MA range with a quarter-cycle time of 4-5 μs. It will drive implosions of heavy liners (typically 50 g) with implosion velocities exceeding 20 mm/μs. Under these conditions very high pressures and magnetic fields are produced. Shock pressures in the 50 Mbar range and pressures exceeding 10 Mbar in an adiabatic compression will be possible. By performing flux compression of a seed field, axial magnetic fields in the 2000 T range may be achieved. A variety of concepts have been identified for the first experimental campaigns on Atlas. These experiments include Rayleigh-Taylor instability studies, convergent (e.g., Bell-Plesset type) instability studies, material strength experiments at very high strain and strain rate, hydrodynamic flows in 3-dimensional geometries, equation of state measurements along the hugoniot and adiabats, transport and shock propagation in dense strongly-coupled plasmas, and atomic and condensed matter studies employing ultra-high magnetic fields. Experimental configurations, associated physics issues, and diagnostic strategies are all under investigation as the design of the Atlas facility proceeds. Near-term proof-of-principle experiments employing the smaller Pegasus II capacitor bank have been identified, and several of these experiments have now been performed. This paper discusses a number of recent Pegasus II experiments and identifies several areas of research presently planned on Atlas.

OVERVIEW OF PEGASUS II FACILITY

Pegasus II is a pulsed-power facility at Los Alamos National Laboratory that is used to conduct a variety of experiments in the high-energy-density regime with applications to the physics of nuclear weapons as well as to basic science. The facility

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consists of 144 energy-storage capacitors arranged as a two-stage Marx bank with a maximum erect voltage of 100 kV. The 4.3-MJ stored energy for this voltage makes Pegasus II among the larger capacitor-bank facilities in the world. The protective damping of the Pegasus II capacitors is provided by fuse packages which are destroyed on each shot. In addition, the highest current experiments on Pegasus II require the use of solid dielectric punch-through switches rather than repetitive use gas-filled rail gap switches. As a result, the turn-around time for Pegasus II is a minimum of approximately one week. Atlas, in contrast, will be resistively damped and use rail gap switches; the resultant simplification in maintenance requirements will actually allow us to reach a predicted shot rate of 100 shots per year. The anticipated increase in shot rate on Atlas necessitates a reevaluation of experimental design, experimental campaigns, and methods of isolating physics issues. Pegasus II is used to produce peak currents as high as 12 MA in cylindrical inductive loads and can be operated either with or without a fast opening switch. In addition to conducting plasma- and hydrodynamic-physics experiments, researchers at the Pegasus II facility continue to address technological issues of developing an efficient switch for eventual use on Atlas. Several different experimental campaigns in support of the nuclear-weapons program are currently being conducted on Pegasus II and involve both heavy, solid liners and thin aluminum foils as the machine loads. The foil targets become plasmas during an implosion; in the foil-implosion experiments the imploding plasma stagnates on the axis of the cylindrical system, and the kinetic energy is converted to thermal energy and radiation. The solid-liner experiments are mainly used to address hydrodynamic issues and often involve the impact of the liner on an internal target package.

SUMMARY OF LINER DESIGN AND PERFORMANCE

Our experimental campaigns on Pegasus II during the past two years have mainly been focused on hydrodynamic experiments that use a standardized solid drive liner. The data from these shots provide a basis for the design of Atlas experiments. On Pegasus II, the active portion of the liner, made from unalloyed (1100 series) aluminum, is a 3.2-g right hollow cylinder (4.8-cm outer diameter, 2-cm height, and 0.04-cm wall thickness) designed to remain at solid-aluminum density during the course of the experiment. For typical Pegasus II operating conditions, the impact of this liner on an internal target with a diameter of a few centimeters results in shock pressures of 100–500 kBar with liner velocities of ~3 mm/μs at a peak current of 6 MA and an impact time of ~10 μs. Present plans for Atlas involve the use of an aluminum cylinder whose mass would be approximately 50 g with typical dimensions of 5-cm diameter, 4-cm height, and 0.15-cm wall thickness. Shock pressures of up to 50 Mbar are expected with liner velocities of ~ 20 mm/μs at a peak current of 40- 50 MA and an impact time of ~ 10 μs.

COMPLEX HYDRODYNAMIC EXPERIMENTS

Using the standard aluminum drive cylinder on Pegasus II, we have conducted a series of experiments to address complex hydrodynamic issues. The experiments often but not exclusively involve the impact of the drive liner on a target package, and the targets have been both in regimes where material strength plays a significant role and in regimes where strength is insignificant. In the strengthless

regime, the experiments offer an approach to studying the vorticity and mixing of materials induced by a shock passing across a nonuniform boundary. Although the details of the target design for an individual experiment vary, one example consists of xenon gas surrounded by three layers; the inner and outer layers are made of lucite and the middle layer, of gallium. The gallium layer is 2 mm thick all the way around, but one half has a smaller radius than the other half. Thus, a step is formed at the junction where these two half-cylinders meet. As the main shock passes across this nonuniform boundary, vorticity and mixing of materials is calculated to occur. We are mainly using axial x-rays to look for the calculated disruptions. Sufficiently high quality x-ray images will provide us with a code benchmark for this particular hydrodynamic phenomenon. Density contours from a two-dimensional hydrodynamic calculation are in excellent qualitative agreement with the data from an axial radiograph. The ability of the diagnostic to resolve small scale vortex structures is clearly critical, and it is anticipated that radiography will be perhaps the most essential tool for understanding physics issues on Atlas. An active program is in place to examine methods for improving the temporal and spatial resolution of the radiographic images and for significantly increasing the number of pictures which can be recorded on a single shot. Target chamber port design for Atlas is taking the radiographic requirements into account.

Material strength plays a significant role in experiments designed to investigate the inner liner surface heating associated with the high strain and strain rate which accompany the cylindrical implosion. For these studies, the development of a sensitive IR pyrometry system has been critical, and successful Pegasus II experiments have recently been conducted at strains of > 100% and strain rates of ~ 10^5 s^{-1}. The liner used in these experiments is significantly thicker than the standard liner to avoid ambiguities associated with Ohmic heating of the inner surface. It is anticipated that Atlas will require similar pyrometric measurements as the strain rate is increased by an order of magnitude. Indeed, there appears to be no other experimental approach to achieving strains of this magnitude. Additional strength experiments have been conducted on Pegasus II using target packages designed by researchers from Lawrence Livermore National Laboratory.

LINER-STABILITY EXPERIMENTS

A series of Pegasus II experiments examining the stability of the imploding liner at near-melt conditions has been conducted. These experiments are motivated by the desire to take full advantage of the Pegasus II facility for performing hydrodynamic studies and to anticipate conditions produced on the Atlas facility. Although one-dimensional calculations show that liners can be accelerated to high velocities with a significant fraction of the liner remaining in the solid state, a more detailed analysis using two-dimensional magnetohydrodynamic codes indicates that the liner may break up as a result of instabilities. To provide experimental tests of these calculations, we have modified standard liners by coating the inner surface of the aluminum with a thin layer of gold to allow for detailed radial radiographic imaging. For some shots, the liner is fabricated with a precisely machined sinusoidal perturbation in the outer surface. Radiographic images provide experimental data on the observed growth rate of the perturbation as a function of spatial axial wavelength; this data can then be compared with theoretical estimates. On two shots to date, a sequence of radiographic images were taken of a liner whose initial

outer surface had sinusoidal perturbations with two distinct axial wavelengths. The data from these experiments will provide added confidence to calculations which account for material strength and its effect on suppressing the growth rate of instabilities. Through this process we will establish credible upper limits to the expected performance of implosion cylinders on Atlas.

MEGABAR EXPERIMENTS

A major limitation on imploding-liner conditions is the rise in material temperature associated with the deposition of Ohmic heat through the high current. Experiments that require ultrahigh-pressure shock generation, greater than the ~300 kBar achieved with standard aluminum liners on Pegasus II, are of interest for weapons research as well as for basic science. One approach to producing such high pressures on Pegasus II involves the use of composite liners. Composite liners may also be a means of extending the achievable shock pressures on Atlas. These systems consist of an outer liner of aluminum with an inner layer of platinum. The aluminum constitutes the bulk of the assembly mass and carries the current. Its low density allows the assembly to achieve maximum velocity. The platinum has a high density and provides for a high shock pressure but remains solid as a result of its high melting point and its relatively low electrical conductivity. With these composite liners, it appears that multimegabar pressures can be achieved on Pegasus II; preliminary results indicate that this approach to high pressures is worth pursuing.

NEAR-TERM PLANS

As the utility of Pegasus II becomes more widely recognized, new experiments and campaigns have been proposed. The present shot schedule includes experiments designed by outside users (from Lawrence Livermore National Laboratory, France, Britain, and Russia) as well as by local researchers. Emphasis for all these experiments is on issues associated with implosions of heavy metal liners, covering physics topics such as high material strain at high strain rates, Rayleigh-Taylor mix/demix, and laboratory production of ultrahigh magnetic fields. Initial experiments on Pegasus II designed to achieve a peak magnetic field of 600 T will involve the compression of an axial "seed" magnetic field by the imploding liner. This flux-conservation approach is similar to explosively driven experiments but has the advantages of a laboratory environment. Successful demonstration of flux-compression field generation on Pegasus II will provide confidence that Atlas can produce the highest laboratory fields in the world, with values as high as 2000 T.

SWITCH DEVELOPMENT

The experiments involving heavy-liner implosions use the Pegasus II facility in a direct-drive mode. Closure of the switches on the capacitor bank couples the current directly to the load through the transmission line. The characteristic waveform for this mode has a peak current at a quarter-cycle time of several microseconds. In the opening-switch mode, the current is allowed to build up to the peak value in a parallel circuit branch and then is rapidly switched to the load. The particular opening switch selected for Pegasus II is a plasma-flow switch;

development of this switch is an ongoing activity and involves detailed evaluation of the behavior of a plasma formed between the two conductors in the vacuum coaxial region near the load. Several Pegasus II experiments have been conducted to test the dependence of switch performance on the mass and configuration of the switch material. Additional experiments are being conducted on a smaller pulsed-power facility to analyze possible sources for lost current in the coaxial region. Successful demonstration of opening switches is important for radiation-production experiments on Pegasus II and on Atlas. The Atlas machine design is based on a modular Marx bank arrangement which will operate at 240 kV for solid liner implosions, but which can be converted to 480 kV operation for driving an opening switch.

APPLICATIONS TO BASIC SCIENCE

Pegasus II has applications to a number of important basic science areas, and the planned Atlas facility will substantially extend these capabilities. The applications extend into the areas of plasma physics, geophysics, planetary physics, astrophysics, and condensed-matter physics. These applications are based upon the capability to produce extreme conditions of pressure, density, magnetic field, and material velocity. As mentioned above, the near-term Pegasus II experiments are designed to reach magnetic fields of 600 T and Atlas could conceivably produce axial fields approaching 2000 T. Field strengths this high can open up new areas of condensed-matter physics. At 200 T, for example, the Zeeman splitting in materials approaches the thermal energy in a solid and substantially exceeds the magnetic-exchange energy. Thus, magnetic properties of materials should be greatly modified in fields this high. At field strengths above 1000 T, the cyclotron radius of a conduction electron in a crystal becomes less than one lattice constant, meaning that the conventional transport properties of materials are field dominated. Some potential experiments include extending present high-field experimental studies, such as magnetization of high-critical-temperature superconductors and cyclotron resonance in low-mobility materials, and moving into new experimental arenas, such as studying new conductivity mechanisms and quantum-limit phenomena in atoms.

Pegasus II also has the capability to achieve very high pressures, both through shock compression and quasi-adiabatic compressions. With Pegasus II, pressures in the megabar regime are possible. Although such conditions are also possible using gas guns and diamond anvil cells, the pressures achievable with Atlas will significantly exceed the limits of other conventional techniques. Among problems of great interest in high-pressure research for Pegasus II and Atlas are understanding the thermal properties of the earth's core materials near the center of the earth (i.e., at pressures in the 3-Mbar range) and measuring the equation of state (EOS) of dense, strongly coupled plasmas (which is of importance to testing models of theoretical plasma physics as well as to benchmarking theories of the interiors of giant planets and brown dwarf stars). Fundamental studies of material instabilities are also being conducted at Pegasus II and will be extended on the Atlas facility.